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Radio galaxies with a 'double-double morphology' – I. Analysis of the radio properties and evidence for interrupted activity in active galactic nuclei

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ABSTRACT

We present four Mpc-sized radio galaxies which consist of a pair of double-lobed radio sources, aligned along the same axis, and with a coinciding radio core. We call these peculiar radio sources 'double-double' radio galaxies (DDRGs) and propose a general definition of such sources: a 'double-double' radio galaxy consists of a pair of double radio sources with a common centre. Furthermore, the two lobes of the inner radio source must have a clearly extended, edge-brightened radio morphology. Adopting this definition, we find several other candidate DDRGs in the literature. We find that in all sources the smaller (inner) pair of radio lobes is less luminous than the larger (outer) pair, and that the ratio of 1.4-GHz flux density of these two pairs appears to be anticorrelated with the projected linear size of the inner source. Also, the outer radio structures are large, exceeding 700 kpc. We discuss possible formation scenarios of the DDRGs, and we conclude that an interruption of the jet-forming central activity is the most likely mechanism. For one of our sources (B 1834+620) we have been able observationally to constrain the length of time of the interruption to a few Myr. We discuss several scenarios for the cause of the interruption, and suggest multiple encounters between interacting galaxies as a possibility. Finally, we discuss whether such interruptions help the formation of extremely large radio sources.

Key words: galaxies: active – galaxies: jets – radio continuum: galaxies.

1 INTRODUCTION

One of the outstanding issues concerning extragalactic radio sources and other active galactic nuclei (AGN) is the total duration of their active phase. For radio sources, this physical age of the nuclear activity is not to be confused with the radiative loss age determined from radio spectral ageing arguments; many extragalactic radio sources probably have a physical age well surpassing their radiative loss age (e.g. van der Laan & Perola 1969; Eilek 1996). The length of the active phase is intimately related to the possible existence of duty cycles of nuclear activity. In cases where nuclear activity is not continuous, how often do interruptions occur and how long do they last?

AGN activity is believed to be associated with the presence of a massive black hole (MBH) in the centre of a galaxy. In the last few years, observational evidence for the presence of such MBHs in nearby galaxies has steadily increased (e.g. van der Marel 1999). Potentially, all these MBHs have the ability to invoke AGN activity; the fact that most are not active (or 'dormant') probably results from a lack of fuel to drive such activity. An important question is whether all galaxies harbouring a MBH went through one or more periods of AGN activity. Franceschini, Vercellone & Fabian (1998) find that multiple periods of activity are not ruled out on the basis of currently available data on MBHs. The timescale for such recurrent activity would, however, be very large, of order 10^9 or 10^{10} yr.

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A duty cycle can only be recognized as such if there is some mechanism to preserve the information of past nuclear activity for a long enough time to be recognized when a new cycle starts up. In extended radio sources, such a mechanism is provided for by the radio lobes, which are large reservoirs of energy resulting from very powerful jet-producing AGN, and which can potentially store information of past activity for a long time after the central activity has stopped. If a new phase of activity should start before these 'old' radio lobes have faded, and if this activity manifests itself by the production of jets, we can in principle recognize this by the observation of a new, young radio source embedded in an old, relic structure.

One well-known candidate for such a 'restarted' radio source is the radio galaxy 3C 219 (Clarke & Burns 1991; Clarke et al. 1992; Perley, Bridle & Clarke 1994). In this source, radio jets have been observed which abruptly become undetectable at some point between the core and the leading edge of the outer radio lobes. Clarke et al. (1992) proposed that the jets in this source could be restarting, but numerical simulations of this mechanism predict structures that have not (yet) been observed (e.g. Clarke & Burns 1991). Bridle et al. (1989) suggested that a restarting jet may also be the cause of some of the peculiar properties of the radio galaxy 3C 288. Since in these sources the new jet activity must have started a relatively short time after the halting of the old jet activity, we prefer to use the term 'interrupted activity' here, as opposed to the above-mentioned 'recurrent activity' which relates to activity phases separated by much larger time-spans.

This paper is the first in a series of three related to possible observed interrupted activity in large radio sources. Paper II (Kaiser, Schoenmakers & Röttgering 2000) presents a detailed model for the evolution of radio sources with restarted jets in which the direction of the jet flow between subsequent periods of activity is similar. In Paper III (Schoenmakers et al. 2000) we present the results of a detailed observational study of one the sources introduced in this paper, B 1834+620 (see also Lara et al. 1999).

Here we discuss four peculiar radio galaxies with morphologies that strongly suggest the occurence of interrupted radio activity. In Section 2 we will present radio and optical data for these four sources. In Section 3 we will argue why these sources form a separate class of radio source, which we will designate as the the class of 'double-double' radio galaxies. We will add a further three sources from the literature which closely resemble the four sources introduced in Section 2. Section 4 contains a brief analysis of their radio properties. Section 5 then discusses possible causes for the observed morphology. We will argue that a restarted jet is the most likely scenario for the formation of the inner structure of these radio sources. Further, we will discuss what may have caused the interruption in these sources, and what other indications there are for interrupted AGN activity. Finally, we will discuss if the formation of extremely large radio sources may be related to this phenomenon. Our conclusions can be found in Section 6.

We adopt $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 0.5$ throughout this paper. A spectral index α is defined according to the relation $S_\nu \propto \nu^\alpha$, where S_ν is the flux density at frequency ν.

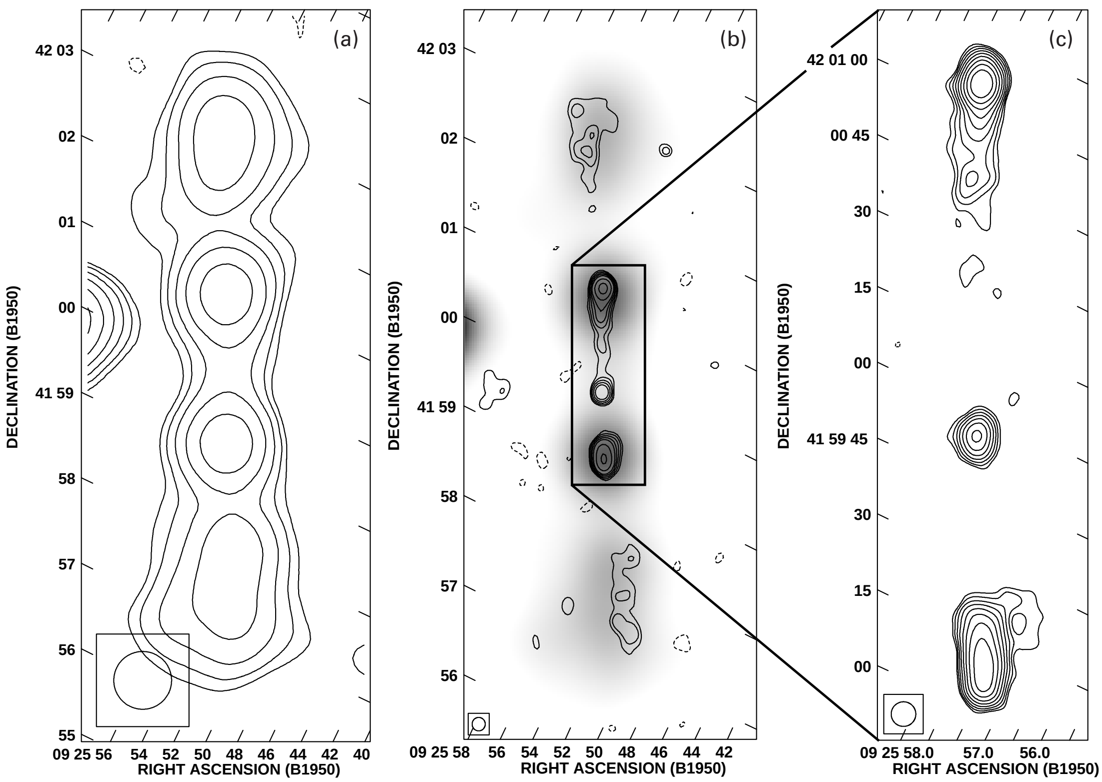

Figure 1. Radio contour plots of the source B 0925+420, rotated clockwise (CW) by 26°. The FWHM size of the restoring beam is indicated in the panel at the lower left side of each plot. (a) Plot from the 1.4-GHz NVSS survey. Contours are at (−1.3, 1.3, 2.6, 5.2, 10.4, 20.8, 41.6 and 93.2) mJy beam^{-1}. (b) Plot from the 1.4-GHz FIRST survey, convolved to a beamsize of 10 arcsec (FWHM). Contours are at (−0.8, 0.8, 1.13, 1.6, 2.26, 3.2, 6.4, 12.8) mJy beam^{-1}. The grey-scale represents the flux density distribution in the NVSS radio map. (c) Contourplot of the inner radio structure from the FIRST survey at full resolution (5.4 arcsec FWHM). Contours are at (−0.45, 0.45, 0.64, 0.9, 1.27, 1.8, 2.55, 3.6, 5.09 and 7.2) mJy beam^{-1}.

2 THE RADIO SOURCES

In this section we present radio and optical data for four sources that we have found in the 325-MHz WENSS survey (Rengelink et al. 1997) during a search for large, extended radio sources. All four sources have similar, peculiar radio morphologies.

2.1 B 0925+420

B 0925+420 (Fig. 1) appears as four well-aligned radio components in the 325-MHz WENSS and 1.4-GHz NVSS (Condon et al. 1998) surveys. The higher resolution 1.4-GHz FIRST survey (Becker, White & Helfand 1995) has largely resolved out the outer two components, indicating a relatively low surface brightness. The inner structure has been well resolved by the FIRST survey, and shows a compact radio core and two lobes with an edge-brightened (FRII-type; Fanaroff & Riley 1974) morphology. The southern inner lobe is more compact than the northern one, and is closer to the radio core. The radio core coincides with a $R \approx 18.3$ mag galaxy on the POSSII survey plates (see Fig. 4a); the magnitude has been taken from the APM catalogue of the POSSI survey, and may be in error by 0.5 mag.

We have taken an optical spectrum of this galaxy with the 2.5-m INT telescope on La Palma on 1996 April 8. We used the IDS spectrograph equipped with the R300V grating and a 1k × 1k TEK-chip. We have used a slitwidth of 3 arcsec, which yields a resolution of ≈15 Å in the dispersion direction. The resolution in the spatial direction is determined by the seeing, and is ≈1.5 arcsec. The total integration time was 1200 s, split into two 600-s exposures to allow cosmic ray removal. The resulting spectrum (see Fig. 5a) shows a strong 4000-Å break and the [O II] 3727 emission line, for which we measure a redshift of 0.365 ± 0.002. The projected linear size of the inner source is ~800 kpc, and that of the outer source ~2450 kpc.

2.2 B 1240+389

The peculiar morphology of this source is best recognized on an overlay of the FIRST and NVSS radio maps (Fig. 2). The inner structure of this source is only marginally resolved in the FIRST survey. Nevertheless, it shows characteristics in common with B 0925+420, such as the diffuse outer lobes and the bright two-sided inner structure. The slightly bend outer structure is also suggestive of a wide-angle tailed (WAT) radio source (e.g. Miley 1980; O'Donoghue, Eilek & Owen 1990). However, in most WAT sources the inner bright spots are not as compact as we see in this source; their brightness decreases more gradually with increasing distance from the radio core. Still, sensitive higher resolution observations of the inner structure would be valuable for determining their radio morphology in more detail. Using a 1200-s *R*-band CCD image obtained on 1997 February 4 with the 1-m JKT telescope on La Palma, we have identified the radio core with a $R \sim 20.1 \pm 0.1$ mag galaxy (see Fig. 4b). We have taken an optical spectrum of this galaxy on 1998 February 23 with the INT. We have used the IDS spectrograph, equipped with 1k × 1k TEK-chip and the R158V grating. We have integrated for 1800 s using a slitwidth of 2 arcsec, which results in a resolution of ~20 Å. We observe a 4000-Å break at an observed wavelength of 5200 Å, yielding a redshift of 0.30 ± 0.01. The spectrum (see Fig. 5b) does not show any emission lines above the noise. At a redshift of 0.30, the projected linear size of the inner structure is ~320 kpc, and that of the outer structure ~860 kpc. We remark that this source is the weakest case of the four sources presented here.

2.3 B 1450+333

The radio morphology of B 1450+333 is best observed on the radio map from the VLA FIRST survey. A contour plot of this map is shown in Fig. 3(b). The outer structure consists of a fat

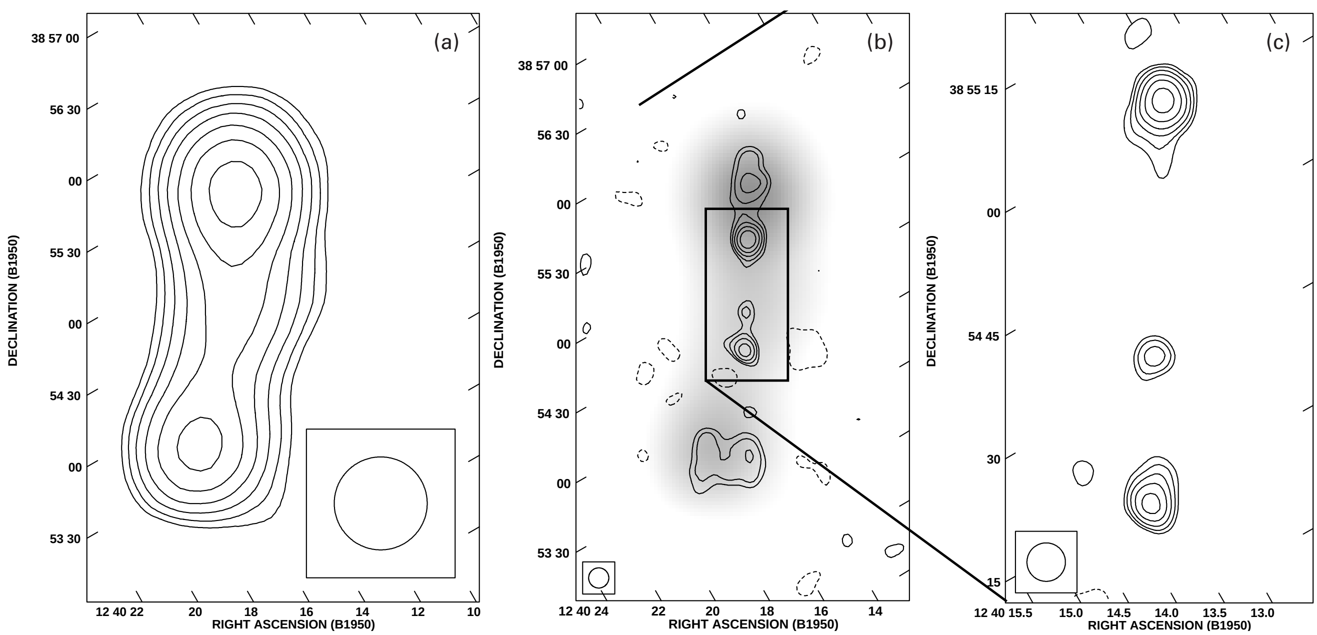

Figure 2. Radio contourplots of the source B 1240+389. The plots have been rotated counter clockwise (CCW) by 23°. The FWHM size of the restoring beam is indicated in the panel at the lower left, or right, side of each plot. (a) Plot from the 1.4-GHz NVSS survey. Contours are at (−1.2, 1.2, 1.7, 2.4, 3.4, 4.8, 6.8, 9.6) mJy beam^{-1}. (b) Plot from the 1.4-GHz FIRST survey convolved to a beamsize of 10 arcsec (FWHM). Contours are at (−0.6, 0.6, 0.85, 1.2, 1.7 and 2.4) mJy beam^{-1}. The grey-scale represents the flux density distribution in the NVSS radio map. (c) Contourplot of the inner radio structure from the FIRST survey at full resolution. Contours are at (−0.4, 0.4, 0.56, 0.8, 1.13, 1.6 and 2.26) mJy beam^{-1}.

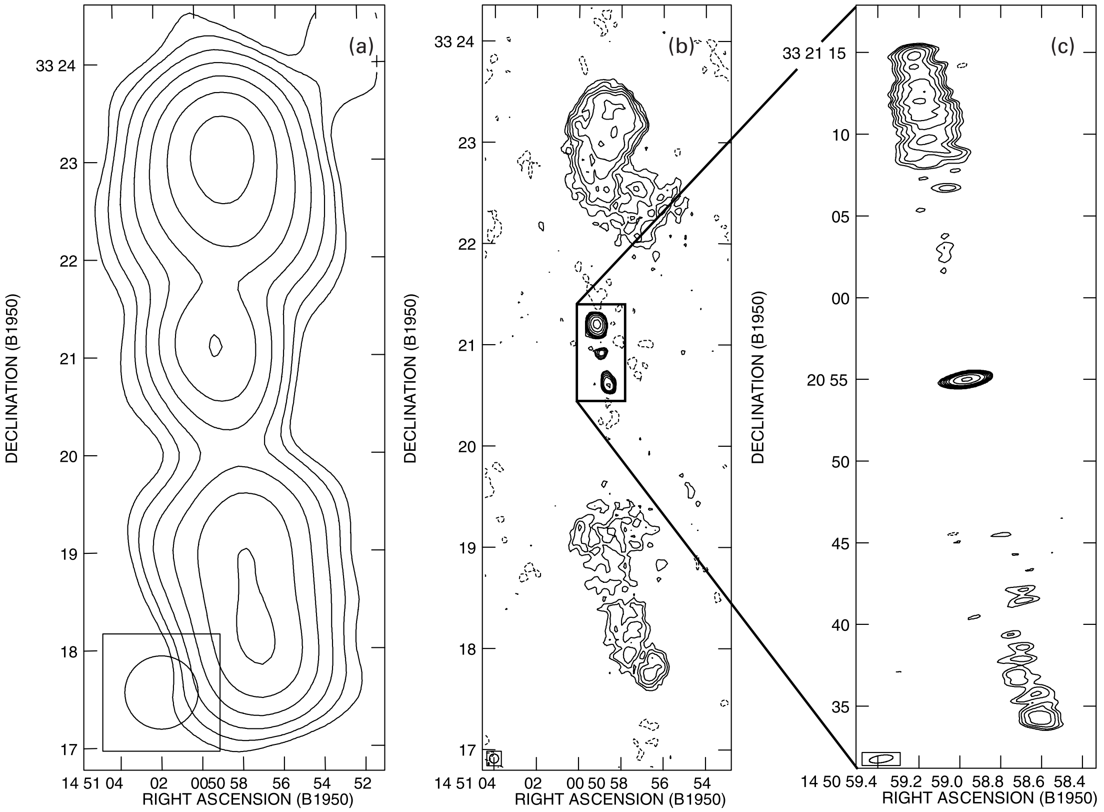

Figure 3. Radio contour plots of the source B 1450+333. The FWHM size of the restoring beam is indicated in the panel at the lower left side of each plot. The FWHM size of the restoring beam is indicated in the panel at the lower left side of each plot. (a) Plot from the 1.4-GHz NVSS survey. Contours are at (−1.3, 1.3, 2.6, 5.2, 10.4, 20.8, 41.6 and 93.2) mJy beam^{-1}. (b) Plot from the 1.4-GHz FIRST survey. Contours are at (−0.45, 0.45, 0.64, 0.9, 1.27, 1.8, 3.6, 7.2 and 14.4) mJy beam^{-1}. (c) Plot of the inner structure from our 5-GHz VLA observations. Contours are at (−0.12, 0.12, 0.17, 0.24, 0.34, 0.48, 0.68, 0.96, 1.92 and 3.84) mJy beam^{-1}.

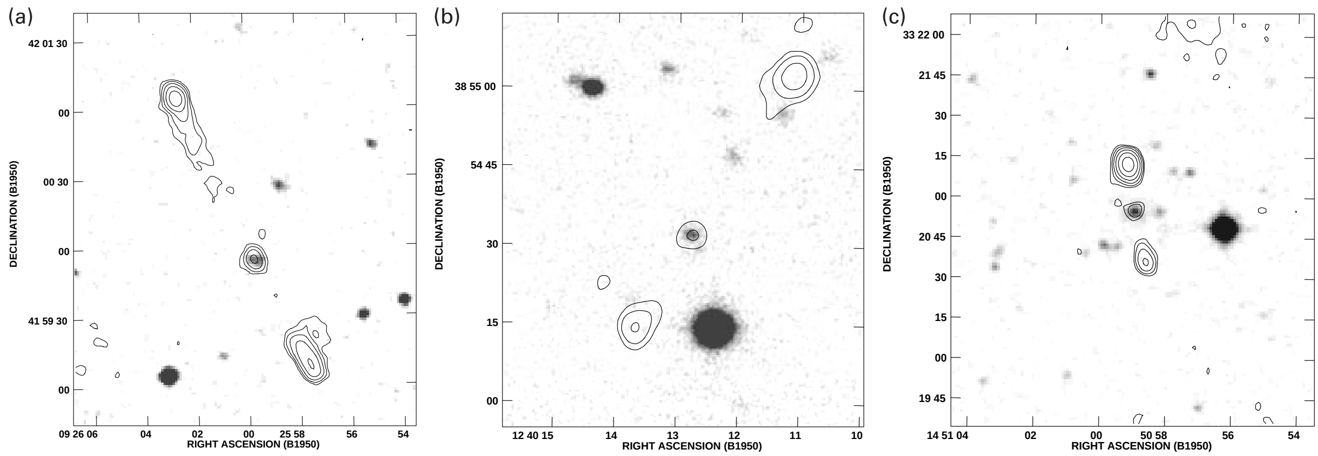

Figure 4. Overlays of the radio contours of the 1.4-GHz FIRST survey and, in grey-scale, optical images. (a) B 0925+420. The optical image is from the POSSII survey. (b) B 1240+389. The optical image is from a 1200-s *R*-band observation with the 1-m JKT telescope on La Palma. (c) B 1450+333. The optical image is from the POSSII survey.

northern radio lobe with no discernible hotspot, and a narrower southern lobe with a weak, possibly double, hotspot. We have observed the inner structure at 5 GHz using the VLA in its BnA configuration. A 20-min observation has been performed on 1998 June 28, using two 50-MHz bands centred at 4835 and 4885 MHz. Flux density calibration was done using 3C 286 as primary flux density calibrator, and using the Baars et al. (1977) values for its flux density. The data have been edited, mapped and phase self-calibrated using the AIPS data-reduction software package. The resulting radio map is shown in Fig. 3(c). The inner radio lobes show an edge-brightened morphology. Similar to the outer lobes, the southern inner lobe is more extended and weaker than the northern inner lobe. The southern inner lobe lies on the radio axis defined by the core and the southern outer lobe, but this is not the case on the northern side of the source; here the northern inner lobe lies well away from the line connecting the core to the peak in intensity in the northern outer lobe.

We have identified the radio core with the brightest of an apparently small group of galaxies on the POSSII plates (see Fig. 4c). Its R-band magnitude, according to the APM catalogue, is $\sim$18.3, with an estimated uncertainty of 0.5 mag. A spectrum of the host galaxy has been obtained by P. Best with the 4.2-m WHT telescope on La Palma, using the red arm of the ISIS spectrograph with the R150V grating and a $1\mathrm{k} \times 1\mathrm{k}$ TEK-chip only. No dichroic has been used in these observations. The integration time is 600 s, using a 2-arcsec-wide slit. The resulting spectrum (Fig. 5c) reveals no strong emission lines in the range between 5200 and 8100 Å. Using the stellar Mgb, NaD and G-band absorption bands, we determine a redshift $z = 0.249 \pm 0.002$. The projected linear size of the inner source is $\sim$186 kpc, and that of the outer source $\sim$1700 kpc.

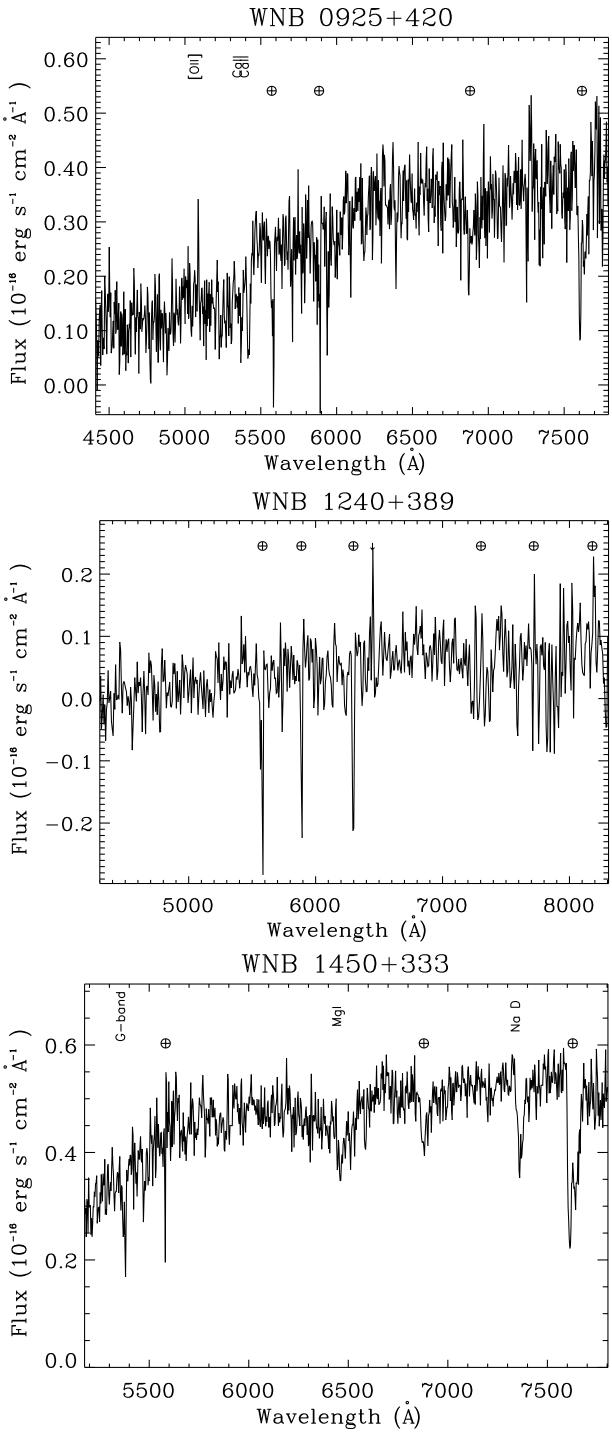

Figure 5. Optical spectra of the host galaxies of B 0925+420 (top), B 1240+389 (middle) and B 1450+333 (bottom). Identified lines have been indicated on the plots. Atmospheric features have been indicated by a '$\oplus$' symbol; those resulting from cosmic rays by a '$\downarrow$' symbol. See the text for details.

2.4 B 1834+620

We have observed the radio source B 1834+620 at a variety of frequencies and resolutions. Radio contour plots, as well as an optical image of the host galaxy and its spectrum, can be found in Paper III. Our 8.4-GHz map unambiguously shows the FRII-type morphology of the outer lobes. Of the two bright inner knots, only the southern one is slightly resolved. The 1.4-GHz map of the inner structure shows that the southern inner component clearly is not a knot in a jet, but an edge-brightened radio lobe (see also Lara et al. 1999). Its morphology resembles that of the outer southern lobe in the 8.4-GHz map. The northern inner component is more compact, but also shows the structure of an edge-brightened radio lobe. Higher resolution 5-GHz VLA observations, also presented in Paper III, show this in somewhat more detail. The radio core coincides with a weak optical galaxy ($R_s = 19.7 \pm 0.1$) at a redshift of 0.5194 ± 0.0002, which is the brightest member of a compact group of three galaxies. The projected linear size is 1660 kpc for the outer source, and 428 kpc for the inner source.

3 'DOUBLE-DOUBLE' RADIO GALAXIES

3.1 Definition

The sources presented in Section 2 are clearly different from 'standard' FRII-type radio galaxies. Since they consist of an inner double-lobed radio structure as well as a larger outer double-lobed structure, we have called these sources 'double-double' radio galaxies (DDRGs). In all the sources presented in this paper the inner and outer radio sources are well aligned, to within 10°. However, there may be double-double sources where this is not the case. Possible examples are the so-called X-shaped radio sources (e.g. Leahy & Williams 1984). In order to incorporate such sources as well, we propose the following relatively general definition of a DDRG: *A 'double-double' radio galaxy consists of a pair of double radio sources with a common centre. Furthermore, the two lobes of the inner radio source must have a clearly extended, edge-brightened radio morphology.*

The sources presented in this paper conform to this definition and are examples of what one may call 'aligned' DDRGs, i.e., sources where the radio axes of the inner and outer structures line up very well. We stress that for the inner structures a clear distinction has to be made between 'knots in a jet' and genuine radio lobes. The definition given above should discriminate against the former cases. For this, high-resolution radio observations will usually be required.

3.2 Other DDRGs in the literature

Adopting the definition of DDRGs in Section 3.1, we have searched the literature for more examples of aligned DDRGs, and we have found three more such sources. They are 3C 445 (B 2221−023; Kronberg, Wielebinski & Graham 1986; Leahy et al. 1997; Wil van Breugel, private communication), 4C 26.35 (B 1155+266; Owen & Ledlow 1997) and 3C 219 (B 0917+458; Clarke et al. 1992; Perley et al. 1994). All three sources have well-aligned inner and outer double radio lobes. The source 3C 219 has a highly asymmetrical inner structure, both in armlength and in flux density. This may partly be the result of an orientation effect. Its optical spectrum (e.g. Lawrence et al. 1996) shows broad emission lines and a non-thermal contribution to the continuum. This is indicative of sources whose radio axis may be close (i.e., $\lesssim 45°$) to the line of sight (e.g. Barthel 1989). Still, its radio morphology agrees with our definition. Also, the source 3C 445 is known to have broad emission lines in its optical spectrum (e.g. Antonucci 1984). However, in this case the asymmetry in the radio morphology and flux density is much smaller.

We further note that other aligned DDRG candidates are the X-shaped radio source 4C 12.03 (Leahy & Perley 1991), which has a small double-lobed inner radio source aligned with one of the two pairs of outer radio lobes. The FRII-type radio galaxies 3C 16 (Leahy & Perley 1991), 3C 424 (Black et al. 1992) and the giant radio galaxy B 1545−321 (Subrahmanyan, Saripalli & Hunstead 1996) also have well-aligned inner source structures. Black et al. present high-resolution observations of the inner structure of 3C 424, which show that this source has, at least on one side of the nucleus, an edge-brightened inner structure. On the other side of the source the situation is less clear. In the other two cases, high enough resolution observations of the inner structures, necessary to determine whether they have an edge-brightened morphology, are not available.

For this paper, we have decided to restrict our sample to the seven sources for which we are confident that they are truly DDRGs, and for which both low- and high-resolution 1.4-GHz radio data are available to measure their radio properties. These are the four sources introduced in Section 2, and the sources 3C 219, 3C 445 and 4C 26.35. We stress that this is by no means a uniform sample of DDRGs.

4 PROPERTIES OF THE INNER AND OUTER COMPONENTS

We have measured the flux densities, projected linear sizes and misalignment angles of the inner and the outer structures of the seven DDRGs at 1.4 GHz. These are presented in Table 1. For the source 3C 445, the FIRST radio map does not allow reliable flux density measurements of the inner structure, since it is embedded in the large-scale outer radio lobes which strongly affect the image quality in the area of the inner structure. The value given in Table 1 is therefore a lower limit. As an upper limit we have taken the flux density of the same area of the source measured in the NVSS survey. Note that because of the extended (outer) lobe emission in this region, this upper limit is a very conservative choice.

We find that all these DDRGs have linear sizes $\gtrsim 700$ kpc. Some DDRG candidates are very large as well [3C 16 ($D = 504$ kpc), 4C 12.03 ($D = 820$ kpc) and B 1545−345 ($D = 1320$ kpc)], although other possible DDRGs such as 3C 424 and 288 have linear sizes of only 100 and 170 kpc respectively. The reason that the seven aligned DDRGs discussed here have a large size may partly be a selection effect: the four sources introduced in Section 2 have been selected to be of Mpc-size. However, the fact that none of the known complete samples of smaller-sized radio sources contain a large number of DDRGs suggests that these are not common among radio sources smaller than ~1 Mpc. Therefore the fact that all seven DDRGs have very large linear sizes is most likely not a selection effect, but probably characteristic of the subclass of radio sources they form.

We have calculated the 1.4-GHz rest frame monochromatic radio luminosities (the radio power). We have assumed that all components emit isotropically, and we have assumed power-law spectra with a spectral index α of -0.75 for the k-correction. In Fig. 6 we have plotted a radio power – linear size ($P - D$) diagram of the inner and the outer structures of the DDRGs. For comparison, we have plotted all $z < 0.6$ 3CR sources in the sample defined by Laing, Riley & Longair (LRL, 1983). We find that, at 1.4 GHz, the inner components of all the DDRGs presented here are less luminous than the outer components. We note that

Table 1. Some radio properties of the seven DDRGs. Column 2 gives the redshift; columns 3 and 4 give the sizes of the inner and outer structures; column 5 gives the difference in the position angles of the radio axes of the inner and outer structure; columns 6 to 9 give the 1.4-GHz flux densities, S, and radio powers, P, after subtraction of the radio core; columns 10 and 11 give the equipartition pressures, p, in the outer and inner lobes. In the case of 3C 445, the flux density of the inner component could not be well determined from the maps of the FIRST survey; the value given is a lower limit, and we have omitted the equipartition pressure calculation for the inner structure. The equipartition pressures are calculated using the method given in Miley (1980), assuming a cylindrical morphology and a filling factor of unity. They are the average of the two sides of the inner or outer structure.

(1) Source	(2) z	(3) $D_{\rm outer}$ [kpc]	(4) $D_{\rm inner}$ [kpc]	(5) $\Delta\theta$ [°]	(6) $S_{\rm outer}{}^{a}$ [mJy]	(7) $S_{\rm inner}$ [mJy]	(8) $P_{\rm outer}$ [10^{25} W Hz^{-1}]	(9) $P_{\rm inner}$	(10) $p_{\rm outer}$ [10^{-13} dyn cm^{-2}]	(11) $p_{\rm inner}$
B 0925+420	0.365	2450	803	3	99	63.7^{b}	5.8	3.7	1.7	7.6
B 1240+389	0.30	860	320	7	24.1	7.8^{b}	1.0	0.32	1.2	40.7
B 1450+333	0.249	1680	180	7	426	33.5^{b}	13	0.98	1.4	61.3
B 1834+620	0.519	1660	428	2	604	200^{c}	84	26	16.7	84.7
3C 219	0.174^{d}	740	90	2	8045	90^{b}	110	1.11	9.6	349
3C 445	0.056^{e}	846	186	2	5260	$\gtrsim 55^{b}$	7.3	0.08	2.6	
4C 26.35	0.112^{f}	730	197	2	962	66.5^{b}	5.4	0.37	1.4	38

Notes: a – Flux density measured from NVSS radio map minus $S_{\rm inner}$; b – Flux density measured from FIRST radio map; c – Flux density measured from our VLA observations; d – Schmidt (1965); e – Hewitt & Burbidge (1991); f – Owen, Ledlow & Keel (1995).

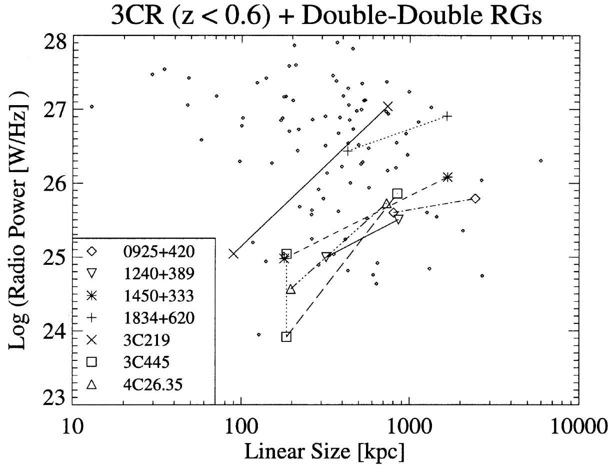

Figure 6. Radio power – linear size ($P - D$) plot of the DDRGs. The radio power is in W Hz^{-1} at 1.4 GHz. For comparison, we have also plotted $z < 0.6$ 3CR sources in the LRL subsample. The larger symbols are the inner and the outer lobes of the DDRGs. Points belonging to a single source have been connected. For 3C 445 we have plotted the lower and upper limits for the flux density of the inner lobes, as discussed in the text.

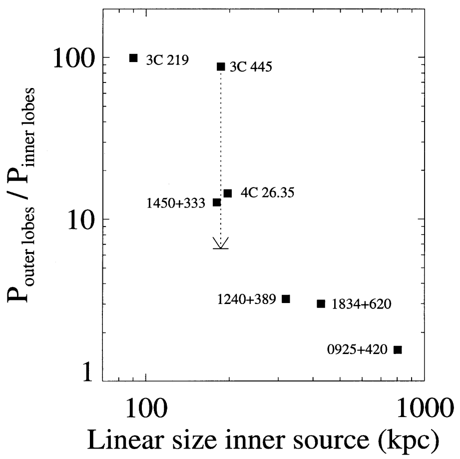

Figure 7. The ratio of the radio powers at 1.4 GHz of the outer to the inner structures of the DDRGs, plotted against the projected linear size of the inner structures. As mentioned in the text, the flux density of the inner structure of 3C 445 is not well determined, and we have plotted the point related to the lower flux density limit only. The dotted arrow marks the range of possible values for this source.

this also appears to be the case for the candidate DDRGs 3C 16, 4C 12.03 and B 1545−345. Further, we find that in almost all DDRGs, except for the source B 1834+620, the radio power of the inner component lies near or below the value separating the radio-luminous FRII-type sources from the radio-weaker FRI-type sources ($\sim 10^{25}$ W Hz^{-1} at 1.4 GHz; Owen & White 1991). Such low radio powers conflict with the edge-brightened morphology of the inner lobes in these sources.

In Fig. 7 we have plotted the ratio of the 1.4-GHz radio power of the outer lobes to that of the inner lobes against the projected linear size of the inner structure. We find that the luminosity contrast between the inner and outer structures appears to decrease with increasing size of the inner sources.

5 DISCUSSION

5.1 Formation scenarios

The two-sidedness and relatively high degree of symmetry of the inner radio structures of the DDRGs strongly points towards a causal connection of the development of the inner structure with processes in the nucleus. Any model for the formation of these sources should, at least, be able to explain the following properties. First, for the inner structure, it should explain:

(i) the two-sidedness and relatively good armlength symmetry;
(ii) the alignment of the radio axis with the outer lobes;
(iii) the edge-brightened radio morphology, and
(iv) the relatively low luminosity as compared to the outer lobes.

Further, in connection to the outer structure, it should clarify:
(v) the large size of the outer structures, and
(vi) the possible presence of hotspots in the outer lobes, such as those seen in B 1834+620.

Here we will discuss three scenarios that may explain the existence of the inner lobes in our DDRGs, all of which have been used before to explain or predict radio structures on different size-scales.

5.1.1 A change in the jet outflow direction

A new radio source may be started by a sudden change in the outflow direction of the jet. At first, the redirected jet will traverse the cocoon, through which it will travel almost ballistically (e.g. Clarke et al. 1992; Paper II), but eventually it will reach the cocoon boundary and run into the much denser intergalactic medium (IGM) again. From that point on, a new hotspot and lobe structure may be created. This may result in the formation of an X-shaped radio source (e.g. Leahy & Williams 1984; Parma, Ekers & Fanti 1985). For the DDRGs presented here, however, we consider such a redirection of the jet flow unlikely to be the cause of the observed source structures, because of the good alignment of the inner and the outer sources.

5.1.2 Backflow instabilities

Structures whose radio morphology may resemble the DDRGs have been found in the numerical simulations of Hooda, Mangalam & Wiita (1994). They simulated the evolution of extragalactic radio jets on time-scales corresponding to 10^8 yr and which propagate out to ~400 kpc. They find that around the time at which the propagation of the head of the jet becomes nearly subsonic, instabilities arise in the backflow of the radio lobe. These instabilities eventually pinch off the jet channel and thus disconnect the outer lobe structure from the jet flow. As a result the original hotspot, and eventually the whole outer lobe, will fade. On the other hand, the pinching of the jet channel gives rise to the development of a new shock front, which after a while may form a new radio lobe-like structure. On the basis of the results of these simulations, Hooda et al. predict a population of large radio sources with diffuse outer lobes and edge-brightened structures interior to these.

Since the jet is pinched off, a good alignment between inner and outer radio structures is a natural consequence. However, in order to pinch the jet channel, instabilities are required which must be strong enough to achieve this. It is rather surprising that something to that effect would happen on both sides of the radio core at roughly the same distance and also at approximately the same time (within a few per cent of the source age), especially since the outer structure of a source like B 1450+333 is highly asymmetric in morphology, so that any backflow in these lobes will have very different properties in each lobe.

Therefore, although this scenario may be able to explain the formation of a one-sided inner structure, we find it unlikely that it can explain the two-sided and symmetric nature of the inner structures of the DDRGs. Note that in the case of 3C 219, which has a highly asymmetrical inner structure, this objection carries less weight.

5.1.3 Interrupted jet activity

Short-term variations in the energy output are known to occur in almost all AGN. In radio-loud AGN, small changes in the jet power may lead to shocks which are visible as discrete 'blobs' in the jet (e.g. Rees 1978), or become manifest only once they reach the hotspot and change its luminosity. For example, the much larger asymmetry seen in hotspot luminosities, as compared to lobe luminosities, in FRII-type radio sources (e.g. Macklin 1981; Paper III) suggests that jet powers vary significantly during the lifetime of a radio source (see Paper III). It is plausible that such variations occur on a large range of time-scales, without seriously disrupting the jet flow.

A complete halting of the acceleration of the jet production in the central engine will be disastrous for the jet channel: the loss of pressure, assumed to be provided by the jet material flowing through the channel (e.g. Kaiser, Dennett-Thorpe & Alexander 1997), will result in its collapse. If the nuclear outflow restarts at some time after the 'old' jet channel has disappeared, it will have to clear out (or 'drill') a new channel through the cocoon. This may result in the formation of a shock at the head of the jet which may manifest itself as a hotspot, under the restriction that the density of the cocoon is high enough to allow such a shock to form.

Analytical models (e.g. Cioffi & Blondin 1992) and numerical simulations (e.g. Clarke & Burns 1991; Loken et al. 1992) predict that the density inside a cocoon is much lower (up to a factor of 100) than that in the original unshocked IGM, which is too low for the formation of a strong jet shock. However, in Paper II we present a model that allows the density in the old cocoon to be much larger than previously assumed, and as a result allows the formation of inner hotspots after the jet has restarted. We show that such a model can fulfil the first five requirements mentioned at the beginning of this section. Whether the requirement of the allowed presence of hotspots in the outer lobes is met depends on the length of time during which the jet production is interrupted; we will return to this topic later.

Only the source 3C 219 cannot be easily explained in this scenario, since the two oppositely directed jets are assumed to restart at more or less the same time, whereas the inner structure of 3C 219 is highly asymmetric in armlength; as mentioned above, another mechanism may be at work in this source. For the other sources presented here, however, interruption of the jet formation is the most promising scenario for their formation.

5.2 Causes and consequences of the interruption

5.2.1 Time-scales of the interruption of the jet activity

A constraint on the time-scale between the halting and restarting of the jet can help in determining the cause of the interruption. In all DDRGs the outer lobes have not yet faded away; unfortunately, this does not provide a very tight constraint, since it is not at all clear for how long a radio lobe will remain detectable after the jet has stopped supplying it with energy. Komissarov & Gubanov (1994) estimate fade-away time-scales of several 10^7 yr for a small sample of currently inactive (or 'relic') radio sources, which is comparable to the time-scale of the activity itself. Therefore this estimate provides only an upper limit to the time-scale of the interruption.

The best example of a radio source in which the interruption must have been relatively brief is B 1834+620, since it still shows a bright and compact hotspot in one of its lobes (Paper III). This indicates that remnants of the 'old' jet must still be arriving in the hotspot, or at least until very recently; the fade-away time of hotspots of size ~10 kpc is estimated to be a few 10^4–10^5 yr (e.g. Clarke et al. 1992; Paper II). Assuming that the radio axis of this radio galaxy has an orientation angle of $\leq 45°$ to the plane of the sky (cf. Barthel 1989) limits the time elapsed since the interruption to less than between 1.1 and 6.4 Myr (depending on the orientation; see Paper III). Since in this amount of time the inner structure must also have formed and grown to its current size, the time-scale of the interruption of the jet must have been close to 1 Myr, at most. Although B 1834+620 is only one example, it shows that if there were a common mechanism for the interuption of the jet activity, it limits the time-scale of the interruption to a few Myr only. Further, it appears as if it starts to operate only after an elapsed activity time of a few times 10^7 yr, since these are the estimated ages of sources as large as the outer structures of DDRGs (e.g. Mack et al. 1998; Schoenmakers 1999). However, the model we present in Paper II suggests that this later requirement is a selection effect: If the interruption occurs much earlier in the lifetime of a radio source, the restarted jet may not be able to form the inner lobes due to a still too low density of the cocoon. Therefore a DDRG would form only when the outer source has grown to a large size. However, if this were the case and the time elapsed between the start and the interruption of a jet is much smaller than the total lifetime of the radio source, then multiple interruptions during a sources lifetime may occur, and it can be expected that DDRGs would be more common among large radio sources.

The DDRGs are not the only radio sources that show evidence for interrupted activity on relatively short time-scales. Several compact and therefore presumably young radio sources have been found that are clearly associated with larger scale radio emission (e.g., B 0108+388, Baum et al. 1990; Owsianik, Conway & Polatidis 1998; B 1144+352, Schoenmakers et al. 1999; B 1245+676, de Bruyn et al., in preparation). The radio structure of these sources can be interpreted as the result of an interruption of the radio activity. If the cause of the interruption not only affects the radio jet formation, but the whole central activity, then it is reasonable to assume that radio-quiet AGN show similar interruptions. Although these sources constitute ~90 per cent of the AGN population, a direct observation of the interruption in these objects is very difficult, since there is no good tracer of past activity on time-scales of a few Myr.

5.2.2 Scenarios for the interruption of the jet activity

In AGN, the formation and properties of jets must be closely related to the properties of the central black hole and its accretion disc, although it is still largely unclear how this is achieved. Assuming that the jet formation is related to the accretion flow, an interruption of the jet formation for a period of a few Myr is most likely caused by a passing event which temporarily disturbs the stability of the accretion disc. There a several scenarios to achieve this, among which are the following.

First, an internal instability in the accretion disc, for instance due to radiation pressure induced warping (Pringle 1997; Natarajan & Pringle 1998). This does not require an external cause for the interruption, but it is unlikely to provide the mechanism needed to explain the DDRGs. First, it is largely unclear what the time-scales are for such a process (Pringle 1997). Also, the occurrence of a warping instability is likely to change the direction of the jet considerably (Natarajan & Pringle 1998). Natarajan & Pringle state that to produce a directional stable jet the central black hole must be spinning, but this also suppresses the formation of a warping instability needed to interrupt the jet formation. This mechanism is therefore unlikely to operate in the DDRGs.

Second, a large cloud of gas may fall into the centre of the galaxy. This may also disturb the stability of the accretion disc and thus the jet formation. However, it is hard to envisage a relation between possible arrival times of such a cloud in the AGN and the large size of the DDRGs unless the arrival of the gas is somehow regulated. The mechanism causing the halting of the jet operates on a typical time-scale of a few 10^7 yr after the jet activity first started. This suggests the following mechanism. If we assume that AGN activity is triggered by an interaction or merger, numerical simulations of colliding galaxies show that these usually do not merge completely in the first encounter (e.g. Barnes & Hernquist 1996). Although the infalling galaxy loses a large fraction of its gas and stars to the main galaxy, parts of it pass the main galaxy. These parts will turn around and collide again with the main galaxy. Simulations show that a typical merger is complete only after two or more of such encounters, which may take up to a few 10^8 yr. Each passage through the host galaxy might lead to a new phase of increased kinematical instabilities in the host galaxy. The turn-around time-scale of the infalling galaxy is roughly comparable to a rotation time of the main galaxy (i.e., a few $\sim 10^7$ yr; Barnes & Hernquist 1996), which agrees with the estimated time-scale between the first start and the ceasing of the jet activity in the DDRGs. On the other hand, substructures in the infalling gas flow may also cause instabilities in the accretion flow; these would then be related to phenomena operating on much smaller time-scales than the turn-around time-scale.

Although the notion that AGN activity may be triggered by a merger event has been around for a long time, there is still no solid proof for this. It is not at all clear how and in what state the gas flows into the inner few tens of pc around the AGN. The scenario we propose depends on a phenomenon which must be quite common in galaxy mergers and interactions, namely multiple encounters between the two galaxies involved. If the first encounter triggers the AGN and subsequent encounters destabilize it, then interruption of the activity must be common among AGN. This may lead to many more sources that are in a restarted phase than are actually observed. The exact behaviour of two merging galaxies depends strongly on parameters as their mass ratio, rotation, relative velocities and orbits. Discussing this in detail extends beyond the scope of this paper, though.

5.3 Possible consequences for the formation of giant radio sources

Some radio sources can grow to sizes of a few Mpc (e.g. Saripalli et al. 1986; Subrahmanyan et al. 1996; Mack et al. 1998; this paper). It has often been suggested that these giant radio galaxies (GRGs) must be very old and/or in extremely low-density environments. However, most indications for this have been obtained by measuring spectral ages (e.g. Mack et al. 1998; Schoenmakers et al. 1999), which may be inaccurate (e.g. Eilek 1996), and by depolarization studies, which are often difficult to interpret (e.g. Schoenmakers et al. 1998).

An alternative formation scenario for these large sources, proposed by, e.g., Subrahmanyan et al. (1996), is that they result from multiple periods of jet activity. The DDRGs presented here suggest that such a formation scenario for GRGs may indeed be valid: if the inner lobes continue to advance at the expected high velocities (see Papers II and III), they will rapidly reach the boundary of the outer lobes and the radio source will evolve further.

In Section 5.2.1 we have discussed several Mpc-sized radio sources which also show inner lobes on much smaller scales (i.e., a few tens of parsecs). Sources such as these may have restarted their jet production only recently and may therefore be progenitors of the DDRGs presented in this paper. Another possible example is the currently largest radio source known in the Universe, 3C 236, with a projected linear size of 5.7 Mpc (e.g. Strom & Willis 1980). It has a bright radio core showing a complex, multiple and apparently young structure on parsec-scale (e.g. Barthel et al. 1985); it is not unlikely that this core structure is the result of interrupted jet activity, as well.

The large number of Mpc-sized radio sources without signs of interruption shows that this phenomenon is probably not necessary to obtain such a large size. Also, a single prolonged period of activity would probably be more efficient in producing a large radio source than one with repeated interruptions of the jet formation. Only in the case that the AGN has run out of fuel, and that a restart results from a new supply of energy, a larger radio source may emerge than that formed during the first phase of activity. The requirement that the outer lobes must still be visible forces such a restart to occur within a few 10^7 yr, which may be achieved by the same mechanism we propose for the DDRGs. Whether this would work repeatedly is hard to imagine, though. Improved statistics on interrupted activity, both in GRGs and in smaller sources, may help us to better understand the influence and importance of this process in radio source formation.

6 CONCLUSIONS

We have discovered four Mpc-sized radio sources which consist of two aligned, but unequally sized, FRII-type radio sources with a coinciding radio core. We have called these sources 'double-double' radio galaxies (DDRGs) and have presented a general definition for this class of radio source. In the literature we have found three more sources (3C 219, 3C 445 and 4C 26.35) that conform to our definition and for which 1.4-GHz radio data are available to us. We have included them into a small sample of seven DDRGs with well-aligned inner and outer radio structures.

We find that all these DDRGs are large radio sources, with linear sizes exceeding 700 kpc. Further, we find that in all cases the inner radio structure is less luminous at 1.4 GHz than the outer structure, and the luminosity contrast appears to decrease with increasing linear size of the inner structure.

We have discussed several scenarios for the formation of the inner structures, and we conclude that an interruption of the jet production in the AGN is the most likely scenario. The detectability of the outer radio structures and the presence of a hotspot in one of the outer lobes of the DDRG B 1834+620 indicate that the time-scale of the interruption must be small, a few Myr at most. Further, we have discussed scenarios for the cause of the interruption. We conclude that multiple encounters between interacting galaxies is a likely scenario, but we note that nothing is known in detail about the consequences of such encounters for AGN activity.

Notwithstanding the cause of the interruption, we believe that DDRGs provide excellent evidence for short (i.e., a few Myr) interruptions of the jet activity in AGN. Detailed studies of the DDRGs are of key importance to learn more about this phenomenon, about duty cycles of AGN, and how these affect the evolution of a double-lobed radio source.

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